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July 30, 1993

MEMORANDUM

TO: Manabu Tagomori, Manager and Chief Engineer
Division of Water and Land Development

FROM: Dean A. Nakano DAN

SUBJECT: Request for Review and Comment on Two Draft Reports Prepared by GeothermEx, Inc. for the Department of Business, Economic Development and Tourism

The Geothermal Project Office respectfully requests your assistance in reviewing and providing comments on the following revised draft reports prepared by GeothermEx, Inc:

1) "Volcanic Hazards to Geothermal Installations in Hawaii: Experience at Geothermal Fields in Volcanic Island Environments"; and

2) "Induced Seismicity and Ground Subsidence in Developed Geothermal Fields: Relevance to Geothermal Development in Hawaii".

I sincerely appreciate your earlier efforts to review the preliminary draft reports and would like to thank you for your comments, many of which have been assimilated within the enclosed draft reports. Any additional input and/or recommendations that you may have will be greatly appreciated.

Thank you again for your continued assistance and should you have any questions, please contact me at 586-2353.

Enclosure

cc: Maurice H. Kaya

DRAFT

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EXECUTIVE SUMMARY

Volcanic hazards to geothermal installation in Hawaii are concerns to developers, financiers, cognizant health and safety agencies and the public. Fortunately, there are histories from other similar volcanic islands where geothermal energy has been developed for many years. Data from these analogous locations have been reviewed and summarized in this report. Experience from most geothermal fields located on islands near geologic subduction zones and plate-impact boundary areas (New Zealand, Japan, the Phillipines, Indonesia, Guadeloupe and Greece), and in continental locations are not analogous to Hawaii. The review provides a method to formulate an objective, if qualitative, analysis of the risk to development of the geothermal resources of Hawaii.

The developed geothermal fields in Iceland and the Acores Islands offer the best available analogies to Hawaii. Many other volcanic areas including Reunion Island, Asal (Djibouti), Mount Pinatubo (Philippines), etc. have been considered; some in Central America offer minor points of comparison. However, either because tectonic setting and petrochemistry differ or because geothermal development has reached only the well-drilling stage, Hawaii appears to be a nearly unique case for study. The case studies of Krafla and Namafjall, Iceland are particularly illuminating. At Namafjall, lava was observed to erupt from a producing well and casings collapsed in several wells during a major volcanic episode. The wells were later repaired at low cost. Power plants continued to operate in Iceland and the fields have been expanded in the face of the eruptive activity. Social acceptance of the symbiosis between volcanism and geothermal energy in Iceland appears to result in aggressive utilization of this valuable resource.

The Hawaiian Islands are comprised mainly of highly fluid basaltic magmas. These magmas give rise to successive lava flows that build shield volcanoes with central craters and secondary flank eruption cones, long radiating fractures and rift zones that are sites of "fountain" and "curtain" eruptions, and long narrow lava flows that extend seaward. Basaltic magmas infrequently produce widespread volcanic cinder and ash fields, viscous lava domes, clouds of fast-moving gas and ash and very large catastrophic subsidence calderas--the most hazardous of volcanism-associated events. A few ash and tuff deposits at Kilauea's summit, Pu'ulena and Kapoho and in the stratigraphic record of the Scientific Observation Holes, show that explosive eruptions may occur in Hawaii and affect developments located in the Kilauea East Rift Zone (KERZ).

From the characteristics of Hawaiian volcanism, the risks to geothermal installations from burial in ash, destruction by explosive shock waves, and of being overwhelmed by clouds of hot gas or mud and rock flows are small. The greater risk is that lava flows may overrun parts of wells, plants, pipelines, utility lines and access roads, that ground fracturing, both from extensional rifting and earthquake shaking, may rupture facilities and access roads, and that lava bombs and/or volcanic glass particles may shower down on the facilities and employee personnel.

Hawaiian eruptive events are highly predictable from instruments measuring inflation and deflation of volcanoes and precursor earthquake swarms. The direction and progress of flows can be forecast. Orderly shutdown of facilities and evacuation of personnel and equipment mitigates against possible damage and injury. Damage to wellheads and pipelines may occur. Plants and equipment which are located to avoid

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the fracture zones and to have the advantage of shielding by topographic high places would be less likely to be damaged.

The following steps can systematically be taken to reduce hazards from volcanic eruptions:

a. Locate well pads, power plants and main auxiliary equipment on topographic high points away from historically active parts of rifts and Pu'us. Locate controls, shops, offices, yards and other support facilities at safe distances from the likely volcanic eruption areas.

b. Design and engineer facilities to withstand maximum earthquake acceleration and intensity factors, utilize modular concepts of construction, and specify equipment with tolerance of ground extension, tilting and subsidence.

c. Establish and maintain an advanced warning system of seismometers, tiltmeters, strain gauges, extension meters and gas detectors to forecast time and site of volcanic activity. Coordinate between Federal, State and operator participants so there is continuous active monitoring, warning and automatic emergency procedures.

d. Shield installations and people form lava flows, bombs and ash falls by topography, berms for at least temporary diversion of flows, reinforced-roofed shelters, ditches/trenches and so forth.

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e. Train all administrative, technical and operational personnel to follow a written volcanic hazard plan. Maintain a continuous "watch officer" schedule to assure efficient reaction to the warning system alert. Keep personnel and methods up to date by periodic drills.

Experience at geothermal facilities elsewhere on volcanic islands indicates that risk to facilities and human life is small. Operations may need to be temporarily curtailed and some facilities may suffer damage that requires replacement and repair, within reasonable economic cost. The geothermal reservoir is not likely to be permanently damaged. In Iceland, geothermal fields have continued to produce electricity during eruptive episodes of some 15 years in duration even though they are exposed to eruptions from less than one mile distant to merely a "stone's throw away".

The potential volcanic hazards may cause damage to facilities and possibly injury to unprotected personnel. However, the typical presence of precursor earthquake swarms, and the probable absence of the violent explosive eruptions associated with silicic/alkalic systems, suggest that there will be sufficient time for orderly shut-down and evacuation, and possibly for the removal of important equipment and supplies before or during a basaltic eruption. Damage to wells and/or pipelines may occur. However, it may be possible to locate power plants and auxiliary equipment at sufficient distance, or to shield them behind natural hills, constructed walls or dug ditches, and thus to protect them. Some equipment and most supplies may be kept in storage far from the area of potential risk. Residential developments should absolutely be precluded from being placed near geothermal plants as they would limit evacuation efficiency and could not themselves be hardened against

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eruption products, thereby interfering with orderly procedures in a geothermal area.

Development of geothermal projects on islands with active volcanism clearly represent an attempt at symbiosis of natural and cultural dynamic events. The developers of geothermal projects in cooperation with the public agencies can mitigate damage and threat to lives and property.

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INTRODUCTION

Many geothermal fields are located coincident with areas of modern volcanic eruption activity. In the mid-Atlantic rift, the circum-Pacific region and elsewhere (figure 1), geothermal fields are present in volcanic island environments which are in varying degrees similar to that of Hawaii. Fields have been developed commercially in the Azores (Portugal), the Aegean Islands of Greece, Guadeloupe (France), Iceland, Indonesia, Japan, New Zealand and the Philippines. Others have been investigated in detail for development in those same countries plus Ascension Island, Unalaska Island (the Aleutian chain of Alaska), Dominica, Martinique (France), Papua New Guinea, Reunion Island (France), Taiwan (China) and elsewhere. Further, the development of certain geothermal fields on the continental mainland has taken place in the immediate vicinity of historically active volcanoes.

The purpose of this study and resulting report is to investigate and use the experience gained from development of geothermal resources on other comparable islands with similar histories of basalt-composition volcanic eruptions to assist and to regulate geothermal development in Hawaii relative to possible volcanic hazards. The experience gained in dealing with volcanic hazards in certain analogous areas, regarding aspects of well and power plant design and construction, and well and reservoir behavior, have relevancy in Hawaii, where geothermal field development is proceeding in an area of historic volcanism.

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GEOLOGIC AND VOLCANOLOGIC SETTING

It is extensively documented that active volcanoes with differing chemistry of magma, located in different tectonic environments, and at different stages of their evolution and activity, behave differently from each other. Therefore, the geology, tectonic setting, and petrochemistry of the Hawaiian volcanoes must be considered when examining possible analogues of volcanic behavior elsewhere. Violence of eruptive activity, velocity of flows, and predictability of eruption are major behavioral characteristics depending on geology, tectonic setting and magma chemistry.

The Hawaiian chain formed as a result of the upwelling of molten material of basaltic composition through an oceanic crust. The upwelling itself probably is caused by a "hot spot", a long-lasting plume of molten material that rises through the crust from the earth's mantle under the force of differential density. The hot spot remains quasi-stationary, while the crustal plate moves over it, generating a chain of volcanic features at the surface. The Hawaiian hot spot is believed to have been active for the past 80 million years. The basic cause of a mantle hot spot is unknown. Several have been identified as being active today at various points on the globe, including (probably) Yellowstone in North America, and (possibly) Reunion Island in the Indian Ocean.

No geothermal field other then Puna, Hawaii has been developed at or near an oceanic hot spot. Exploration, but not development, was carried out on Reunion. The closest development analogy probably is an oceanic rift zone (figure 1), such as is present at Iceland and the Azores, and which produces mafic (basalt) magma, similar to Hawaii.

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Continental rifts (East Africa and the Rio Grande) and continental hot spots (Yellowstone) are not suitable analogies, because vast quantities of silicic continental crust become involved in the magma-generation process. Therefore the processes and products of this bimodal basaltic-silicic volcanism are dissimilar to those of basaltic oceanic rifts and oceanic hot spots.

Certain places where oceanic rifts or triple junctions (where three rift arms meet) have begun the process of breaking up a continent, such as the Red Sea and the Afar region of Ethiopia and Djibouti, can serve as analogues to oceanic hot spots during certain phases of the rift development and evolution. Unfortunately, there is no operating geothermal field for comparison, although there has been exploratory drilling in both Ethiopia and Djibouti.

Therefore, developed geothermal fields in Iceland and the Azores, both oceanic rifts, offer the best available analogy to Hawaii (table 1); experience in exploring and drilling the Reunion hot spot and the Asal, Djibouti triple junction are of secondary importance. Geothermal fields located where one impacting plate has been pushed down beneath another ("subduction"), such as Miravalles, Costa Rica and Momotombo, Nicaragua, may provide minor points of comparison.

In general, however, the experience from most geothermal fields located in island settings near subduction zones or other plate-impact boundary areas is not relevant to Hawaii. This includes the geothermal development in New Zealand, Japan, the Philippines, Indonesia, Guadeloupe and Greece. Geothermal developments in continental locations (the mainland United States, Italy, Kenya, Turkey, China, etc.) often are non-volcanic in setting; even where volcanism is involved there is no analogy to the Hawaiian situation.

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VOLCANIC HAZARDS IN AN OCEANIC RIFT AND HOT SPOT

Islands built up by volcanic eruptions at an oceanic hot spot or along an oceanic rift typically are largely basaltic in composition. The basaltic magma, being deficient in silica, is highly fluid. Locally, at major volcanic centers along the rift, there may be differentiation of magma such that silicic or alkalic volcanic rocks form at a late stage of evolution of the system. This can be significant, because the processes and products of silicic/alkalic volcanism are significantly different from those of basaltic volcanism, even in comparable oceanic rift or hot spot environments.

The Hawaiian chain is notably poor in silicic and alkalic volcanic differentiates, perhaps because the oceanic crustal plate moved too rapidly over the hot spot to allow much in situ magma differentiation to occur. The products of the essentially basaltic Hawaiian volcanism are:

(a) The development of enormous, sometimes coalescing, shield volcanoes around a central crater, built up by numerous successive lava flows (for example, Mauna Loa).

(b) Formation of relatively small areas of collapse around the central crater ("calderas") as a result of withdrawal of magma from the supply chamber underneath the volcano.

(c) The development of innumerable smaller, secondary eruptive cones on the flanks or at the base of the central volcano, composed of lava flows and coarse cinders.

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(d) The development of long, narrow swarms of semi-parallel surface cracks or fractures ("rifts"), typically radiating out as arms from the central volcano, through which lava may erupt to the surface or into which molten material may be injected from below and solidify ("intrusive dikes").

(e) Long, narrow lava flows, often extending several miles from their crater, vent or fissure source, sometimes reaching to the sea, and often having long, hollow, internal tubes through which the lava moved.

These may be present undersea as well as on the earth's surface. In addition, submarine volcanism may result in the formation of glassy cinders and ash. However, submarine processes and features can be ignored in a discussion of geothermal field development.

Notably absent from this basaltic assemblage are the principal products of silicic and alkalic volcanism:

(a) Thick, widespread fields of fallen volcanic ash and cinders ("tuff") around and downwind from the central vent. Some ash and tuff deposits have been observed at Kilauea summit. Pu'ulena and Kapoho, and thin beds of ash were found in the cores of the Scientific Observation Holes. Minor phreatic explosions may occur where lava intersects the ground water table.

(b) Thick, widespread flows composed of lava, mud, and loose rock ("lahars"), often accompanied by localized landslides and rockfalls.

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(c) Domes of viscous lava that rise from and solidify several tens or hundreds of feet above a central crater.

(d) Hot or incandescent clouds of gas and ash, moving downslope at high velocity.

(e) Very large calderas, whose areas are measured in dozens or scores of square miles, formed from the explosive evacuation of large subsurface chambers.

The products of basaltic volcanism are, therefore, more likely to be highly fluid, less viscous, better able to release their entrained gases quietly and steadily, and less explosive, than silicic or alkalic volcanic products. Basaltic products are more likely to erupt as lava fountains and to spread widely as fluid lava flows, with much less airborne debris. By contrast, silicic and alkalic magmas are more likely to be explosive, with great quantities of airborne ash, cinders and entrained gases. Lava flows are of lesser volume, and they usually are viscous, have shorter flow paths, and form steeper-sided edifices than do basaltic systems. They are more likely to be accompanied by secondary lahars, mudflows and landslides.

From the foregoing, it is therefore statistically unlikely that geothermal installations on Hawaii will be buried deeply in ash, hit by severe explosive shock waves, or smothered by clouds of incandescent and hot gas, or by walls of mud and rock. There is the risk that:

(a) Lava flows from some close or distant eruptive center may overrun parts or all of the installation or its access way.

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(b) Rifting, with or without accompanying dike intrusion or lava eruption, may offset, rupture or damage parts of a geothermal installation or its access way.

(c) Facilities may receive a light bombardment with cooled chunks of lava ("bombs"), glass particles coming from a lava fountain located at some distance from the installation, or ash.

The potential volcanic hazards may cause damage to facilities and possibly injury to unprotected personnel. However, the typical presence of precursor earthquake swarms, and the probable absence of the violent explosive eruptions associated with silicic/alkalic systems, suggest that there will be sufficient time for orderly shut-down and evacuation, and possibly for the removal of important equipment and supplies before or during a basaltic eruption. Damage to wells and/or pipelines may occur. However, it may be possible to locate power plants and auxiliary equipment at sufficient distance, or to shield them behind natural hills, constructed walls or dug ditches, and thus to protect them. Some equipment and most supplies may be kept in storage far from the area of potential risk. Residential development should absolutely be precluded by zoning from being placed near geothermal plants as they would reduce evacuation efficiency and could not themselves be hardened against eruption products.

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CASE HISTORIES FROM COMPARABLE ENVIRONMENTS

The most important history of volcanic damage to a geothermal field, in terms of tectonic setting and development comparable to Hawaii, is that of the Krafla-Namafjall area, Iceland (figure 2). However, other Icelandic geothermal fields in similar volcanic settings (table 2) have not experienced volcanic damage. Minor volcanic damage once was reported at the Momotombo, Nicaragua geothermal field. Recent volcanism and the potential for future volcanic damage is evaluated for the geothermal fields in the Azores, Djibouti and Reunion. A case in Costa Rica wherein hydroelectric facilities were constructed during continuous volcanic eruption is described. An area in the Philippines (Mt. Pinatubo) had undergone geothermal exploration and drilling prior to the volcanic eruption, but this represents a very different geologic setting. Volcanic activity not analogous to the volcanological setting of Hawaii were not described as detailed case histories within this report.

Krafla and Namafjall, Iceland

Krafla volcano and geothermal field are located in the volcanically active central rift zone ("neovolcanic zone") of northeastern Iceland (figure 3). Basaltic lavas of middle and late Pleistocene and Holocene age (0.7 million years or younger) fill the central rift. They are in turn cut by swarms of fractures trending NNE-SSW, which are product of the active rifting process. Into these fractures have been intruded numerous dikes, also of basaltic composition. Locally, large volcanic edifices have been erected by continued, localized lava eruption. Some of these, at least in part, are differentiated to silicic composition. Calderas and related collapse features, up to 5 or 6 miles in diameter, have formed around two major edifices, one of which is Krafla. The Krafla caldera formed after the explosive ejection of a silicic tuff. Intense fumarole activity is reported from many locations.

A portion of the Krafla volcano, an eruptive center known as Leirhnjukur (figure 4), had erupted extensively during the years 1724-1729; this was so impressive a set of fissure flows and lava fountains that it became known in Icelandic folklore as the Fires of Myvatn (named for a nearby lake). Other nearby volcanoes also show evidence of very youthful activity, both in their central edifices and in fissure dike swarms. Despite this, Icelanders drilled geothermal wells at Namafjall, located about 4 miles SSE of Krafla (figure 4), within the active rift, beginning in the late 1960s. The 3 MW Namafjall geothermal plant came on line in 1969 and has continued for almost 25 years to supply electricity to a commercial diatomite-mining operation at Lake Myvatn.

In 1970, geothermal exploration began at Krafla. Despite the fact that only three wells (one successful) had been drilled, a decision was taken suddenly in 1975 to build a 30 MW geothermal power plant at Krafla, in order to avoid an anticipated electric power shortage in the northeast. Drilling, well testing, power plant design, and construction of facilities went on simultaneously. The 30 MW plant was completed in 1977; only 7 MW of steam was available at start-up.

The causes of this steam shortfall are complex. In December 1975, Leirhnjukur began erupting, less than two miles from the power plant (figure 4), after a quiescence of over two centuries. Eruption was accompanied by several major episodes of surface rifting and dike emplacement, extending south through the Namafjall area. Volcanic eruptions and rifting continued intermittently for more than nine years.

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Well damage occurred and production from four wells at Krafla reportedly decreased sharply. The five original wells at Namafjall also were reportedly damaged. It is still unclear whether, or to what degree, this damage reflected a change of conditions within the reservoir, perhaps as a result of dike emplacement, or to what degree the damage reflected transient conditions.

An Icelandic engineer, (Thorhallsson, 1988) has described the events and their results:

> "....The Krafla eruptions broke out....some 2 km away from where the walls of the power plant were being poured. The Krafla events have seen 20 cycles of uplift and rapid subsidence, which is caused by inflation of a shallow seated lava chamber. Once a certain pressure or elevation of the ground is reached, rifting takes place and the lava is unloaded into new fissures. During nine such events volcanic eruptions have broken out along the fissures, lasting from several hours to a few days. At the time of the first eruption....only five wells had been drilled and the power house was in the early stages of construction. At this point it was debated whether the project should be postponed, but it was decided to continue the work in spite of the uncertainty about continued eruptions. Installation of one of the turbines took place on schedule in 1977, but the other one was kept in the boxes....The power house has served as a good tilt-meter to monitor this activity, tilting over 20 mm over a length of 70 m....Wells have been damaged due to ground movement associated with the Krafla eruptions 1976-1985. The total tilting across the geothermal field was 1 m and a subsidence of 1 m passing through the geothermal field at Bjarnarflag 10 km to the south damaged the

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> five production wells that served the Icelandic Diatomite Co....factory and the 3 MW_e power plant....Incredibly one of the wells actually produced an eruption. Well 4 at Bjarnarflag was spouting molten lava for a short period in 1977! First the elbow of the wellhead was eroded away, and then the red glowing lava came out, producing about 10 m^3 of a very porous and friable scoria. Casing damage was observed in two wells at Krafla that are only some 2 km from the eruptive center....The production casing collapsed in three wells, and these have been repaired simply by milling the collapses away."

Well No. 4 was about 1,200 meters in depth. It was found to be plugged below about 600 meters depth after the eruption, but has continued in use at a reduced capacity (Eliasson, Einar, 1992, personal communication to DBEDT) after minor repairs to the wellhead.

The report of lava erupting from a well has been described independently by U.S. Geological Survey volcanologist Robert Decker (Decker and Decker, 1981)::

> "..... one of these rifting episodes occurred on September 7, 1977. An earthquake swarm was followed in rapid succession by a brief but spectacular volcanic fissure eruption and ground cracking parallel to the rift. In a zone about 2 kilometers across and 20 kilometers long, the cracking formed open fractures up to 20 centimeters wide with vertical offsets as large as one meter.... One of the cracks cut through a producing geothermal steam field. Some magma must have been injected along this fracture, for one of the steam wells erupted brief spurts of incandescent lava. The erupting lava-

cut through the heavy metal pipe at the well head and showered a few tons of frothy lava fragments around the well. This is the only known case where lava has erupted from a man-made vent.... A fracture somewhere between the surface and the 1,200-meter depth of the well broke the well casing and allowed a small amount of molten rock to enter the producing well. The steam lifted the magma spray to the surface..."

Although Decker attributes this occurrence to Krafla, there is evidence that his description instead refers to wells at nearby Namafjall (Bjarnarflag sub-area), as described by Thorhallsson.

However, the results were not as disastrous as first impressions would indicate. Although the rifting-eruptive process continued for some years thereafter, drilling and well testing was resumed at Krafla in 1978, one-half mile farther to the SE from Leirhnjukur crater and its associated fissures (figure 5). The mass flow rate from the first well was disappointingly low, perhaps because the well was outside of the main fracture zone (or perhaps, as some believed, because of damage to the reservoir).

After further study, and despite the risk of continued rifting and eruptions, drilling began again in 1980 and continued through 1983, representing 13 new wells or redrills of existing wells. Some of the new wells were drilled to the south of the power plant and others were located still farther to the east of the original production wells (figure 5). Almost all of these were productive, and the Krafla wells are now capable of supporting the 30 MW power plant. A second 30 MW plant now is under consideration.

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The daily operation of the power plant, located in the active fissure zone, was not disturbed by the eruptions and fissure offsets (Eliasson, 1992). Significant corrosion of turbine blades was reported in 1980, perhaps as a result of an increase in the acidity of the produced steam. The turbines have passed routine inspections in subsequent years without evidence of excessive wear or corrosion.

As reported by Thorhallsson (1988), the Namafjall field, 4 miles to the south, also was cut by volcanic fissures during the 1977 eruptive episode. All of the pre-1977 wells at Namafjall subsequently have been retired, and two newer wells supply the 3 MW power plant. A reason given for their retirement is that fissuring caused increased permeability in the zone from the surface to about 600 m depth. The resulting reduction in pressure in turn caused rapid boiling in the shallow reservoir zone. This, in turn, cooled the upper reservoir. Thus, although the wells sustained no direct damage, they soon became inefficient producers. Thorhallsson (1988, quoted above) implied that ground subsidence damaged the five production wells at Namafjall.

Thorhallsson's explanation of the cause of damage to the Krafla wells is somewhat different: "....The chemistry of the fluid at Krafla was also upset. Volcanic gases were injected into the reservoir fluid causing rapid calcite scaling in the upper reservoir, and a reduction in permeability in the lower reservoir...."

Not surprisingly, there is no broad agreement within the Icelandic scientific community as to whether any permanent reduction in reservoir permeability resulted from this episode of fracturing and lava intrusion.

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The Krafla-Namafjall fissure eruptions and their effects upon the geothermal wellfields located astride the fissure zone represents the closest historical analogue to what might occur in a possible eruption in or near a geothermal wellfield in Hawaii. However, the high-temperature geothermal fields of Reybjanes, Hengill and Svartzengi (Table 2), all located within the active Neovolcanic Zone, have not been subjected to either rifting or volcanic eruption during the tens of years that they have been explored and drilled.

Agua de Pau, the Azores

The Agua de Pau geothermal field (3 MW installed, 10 MW under development) on São Miguel Island, the Azores (Portugal) is the only other developed geothermal field located on an oceanic rift zone, besides those on Iceland. Volcanologically, Agua de Pau is highly differentiated, and therefore exhibits many of the characteristics, and possibly the risks, of a silicic magma. Volcanically induced mudlfows or landslides are possible, as are explosive shock waves, incandescent gas clouds, and ash falls. However, there is also the risk of lava flowing from the central crater or from a fissure high on its flanks, located topographically above the geothermal field, at a distance of 2 or 3 miles.

There are in addition several small basaltic cones on the lower flanks of the volcano, at least two of which have erupted in historic times (1564, 1652). These produce very fluid lavas, capable of traveling for miles. Indeed, one lava flow in the 16th Century buried part of a village located downslope a few miles to the north. This flow may, however, have come from the area of the central crater, rather than from one of the subsidiary cones. Also, the subsidiary cones are at lower elevations than the geothermal wells, and thus pose a minimal

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risk. A basaltic eruption at a higher elevation on the main volcano remains the major potential threat.

Reunion Island

Reunion Island, an overseas territory of France located in the Indian Ocean, is believed to be an oceanic hot spot, even though it is located near the rift spreading center of the Indian Ocean. In either case, whether hot spot or oceanic rift, it presents a close volcanological analogue to Hawaii.

The island is dominated by a basaltic shield volcano (Piton de la Fournaise) which has erupted almost continuously during historic time. Approximately 150 separate eruptive events are recorded in the 350-year period beginning 1640, several of these being multi-year-long eruptive sequences. (The further back in the historic record, the less likely it is that individual eruptive events are separated out of an eruptive sequence, even if there were long pauses in the sequence.) The eruptions principally have taken the form of lava flows from a central crater, from fractures radiating or extending in linear fashion from the central crater, and from subsidiary eruptive cones. Lava lakes have formed within craters on several occasions; on rare occasions lava domes have formed within a crater.

Scientists of the Bureau des Recherches Geologiques et Minieres (BRGM) have conducted geothermal exploration extensively on Reunion, and have drilled at least one deep exploratory hole. This was unsuccessful, for reasons not stated. Because of the combination of lack of success and potential volcanic hazard, the project was suspended indefinitely. However, the BRGM scientists expressed the belief that geothermal electricity could be developed on Reunion at an acceptable level of risk, by utilizing the historic and geologic record as a guide to the placement of wells and power generating facilities.

Asal, Djibouti

Lake Asal is in an active spreading center located close to one of the arms of the Afar triple junction. Intensive rifting has created a structural depression mostly below sea level that contains the lake, and that is separated from an arm of the Red Sea by a few low volcanic hills. The rift is filled with basaltic flows and intrusive dikes, and cut by numerous fissures, several of which are currently fumarolic. Sea water is believed to enter the rift through certain fissures, thereby helping to maintain water in Lake Asal.

The volcano Ardoukoba erupted in 1978 along one of the central fissures, building a central edifice, with flows extending for several miles towards Lake Asal. Previously, in 1975, two geothermal wells had been drilled within the rift, near its southwestern border, some four miles from the eruptive site. No damage was reported to the wells, which are at a significantly higher elevation than the volcano. Subsequently, in 1986-1987, a series of four additional wells was drilled in the rift. One of these was approximately one-half mile closer to the volcano, but still at higher elevation.

There has been no volcanic activity since 1978. However, the possibility of further fissure eruptions, perhaps accompanied by eruption of bombs and glassy ash, is recognized. Development of a 15 MW field is under consideration. The wells, power plant and auxiliary facilities are expected to be some 500 to 800 feet higher in elevation than the present summit of Ardoukoba. The possibility exists that other sections of the active rift will open and erupt, or that Ardoukoba will build a significantly higher edifice through subsequent eruption.

Because of its location at the ocean-continent interface, and because all of the geologically recent products of volcanism in the area have been basaltic, the Asal field is considered to be a possible analogue to Hawaii.

Momotombo, Nicaragua

The geothermal field (65 MW installed capacity) is located on the lower slopes of an andesitic stratovolcano (Momotombo) that erupted last in 1905. During the early years of field development (perhaps 1976-77), a well pad was constructed several hundred meters higher up the mountain, for purposes of exploratory drilling. There is then reported to have occurred a series of minor earthquakes, supposedly of the volcanic precursor type. The earthquake(s) reportedly caused a rock slide or mud flow on Momotombo that buried the drill pad. No injuries were reported. There is no published documentation of the event or of its volcanic nature; the episode thus might as easily represent a landslide caused by a tectonically induced (non-volcanic) earthquake. The region is seismically active. Geologically, Momotombo is very different from the Hawaiian volcanoes; therefore the analogy is weak and the correlative risk is minor.

Other Areas

Non-volcanic landsliding is capable of damaging or destroying geothermal installations. The casing of one well at The Geysers geothermal field was sheared as a result of the failure of natural slope formed of hydrothermally altered rock. A similar event occurred at the

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Zunil, Guatemala geothermal field (15 MW planned for construction) in 1991, with some loss of life and with damage to one wellhead and to miscellaneous structures. No volcanic process was involved in either of these natural events, despite press reports to the contrary. Because Zunil and The Geysers represent very different geology and topography than Hawaii, these episodes are not considered to be representative of risk at the Puna geothermal field.

Geothermal exploration and well drilling also had taken place at Mt. Pinatubo, the Philippines, some years in advance of that volcano's explosive eruption in 1991. The volcano had last erupted 300 years previously, and was not considered to be a risk by the Philippine government authorities that approved and conducted the geothermal exploration. The wells drilled in the exploration program were destroyed by the eruptions. No further work is contemplated in the area. However, the tectonic setting and petrochemistry of Mt. Pinatubo are so different from Hawaiian volcanoes that no further inferences are warranted.

Construction of a 50 MW geothermal power plant is underway at Miravalles field, Costa Rica. Both Miravalles and adjacent Rincón de la Vieja volcanoes have been active historically, Rincón de la Vieja most recently in 1970. Both are andesitic stratovolcanoes, similar to Momotombo, but unlike the Hawaiian chain in geology, chemistry and setting. Volcanic landslides and mudflows may occur at some unknown future date, along with the possible deposition of ash blankets, and possible explosive shock waves or hot gas clouds. By contrast, highly fluid lava flows or lava fountains are less likely in the vicinity of the wellfield and power plant. There are plans to construct a second 50 MW plant later this decade, indicating some confidence on the part of the Costa Rican authorities that the risk to the geothermal facility is not great.

Also in Costa Rica, a major hydroelectric dam, power plant and penstock were constructed in the middle 1970s on a river immediately adjacent to Arenal volcano, despite the fact that the volcano was in continuous eruption throughout most of the construction period. Care was taken during the design phase to place structures upwind from the volcano, to minimize the possibility of large ashfalls; and many structures were located on high ground or behind small hills, to minimize the impact of lava flows, explosive shock waves and/or volcanically induced mudflows. Operations apparently have been free from volcanic impact. Arenal continues to be active periodically.

There have also been phreatic eruptions of steam, mud and rock from several geothermal areas in recent years, including developed fields at Tiwi, the Philippines and Ahuachapán, El Salvador. These are non-volcanic phenomena in the strict sense, as they represent explosive reactions between groundwater and eruptive material. Escapes of toxic gas clouds also represent a hazard in some geothermal areas. One such event took place about 20 miles distant from the partially developed Dieng geothermal field, Java, Indonesia, in 1979, resulting in the death of about 150 local inhabitants. However, here again, no eruptive activity was involved. In all of these cases there is no parallel with geologic conditions in Hawaii.

Volcanic eruptions have caused great loss of life, injury, and damage to property in many other areas where no geothermal operations have taken place. These are not discussed herein, despite their magnitude, because they do not represent the volcanic conditions of the Hawaiian Islands.

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RISK MITIGATION

From the foregoing, the principal volcanic hazards to geothermal development in Hawaii are, in probable decreasing order of severity or likelihood:

- Rifting through the geothermal facility: possible damage to or rupture of wells and pipelines; possible eruption of lava or ash fragments through or alongside of damaged wells; possible damage to or destruction of power plant and auxiliary equipment by rifting or by lava emission; possible downing of power transmission lines; mitigation depends upon intensity, extent, exact location and duration of the rifting episode, and the quantity of lava erupted.

- Overrunning by a lava flow from an eruptive center: possible damage, destruction or burial of wells, pipelines, power plant, and auxiliary equipment; mitigation depends upon location, quantity and velocity of flow(s), and upon defensive measures taken for equipment before the flow(s) arrive.

- Bombardment by cooled lava fragments or glassy ash: possible impact damage to structures; mitigation depends upon number, size and terminal velocity of bombs, and upon protective measures such as design and shielding taken in advance.

- Shaking caused by volcanic precursor earthquakes or by eruptive shock waves: possible damage to structures;

mitigation depends upon magnitude, site acceleration and site intensity of earthquakes, and upon design characteristics of the facilities and their distance from the epicenter(s) or eruptive center.

Mitigation of risk from these hazards is possible as mentioned for each case, based upon the principles of:

- location
- distance
- design
- advance warning
- shielding
- training

Location. To the degree possible, well field and power plant facilities should not be constructed within the active rift or directly down-drainage from a known or presumed active volcano. This may involve directional drilling from pads located just off of the main rift zone, and similar placement of the power plant, gathering system, power transmission lines and main auxiliary equipment.

Distance. It may be possible to construct storage facilities, offices, workshops, remote controls, and back-up facilities at some distance from the geothermal field, especially at sites sheltered from the most likely volcanic hazards.

Design. Facilities should be designed to withstand the maximum likely earthquake (ground acceleration and intensity of shaking), should be made of fire-resistant materials, and should, to the degree feasible, be of modular design for easy and rapid decoupling and removal of expensive or critical pieces of equipment. Installed equipment should have high tolerance to ground tilting and/or subsidence.

Advance Warning. Precursor earthquakes occur in almost all cases of eruption, surface fissuring and/or dike injection in oceanic rifts and hot spots. In Hawaii, either there should be a continuous link established with the Hawaiian Volcano Observatory, or an independent, state-managed, operator-funded network of seismometers, tiltmeters, strain gauges and/or gas detectors should be installed locally, to identify precursor swarms and to forecast site and time of volcanic activity. In advance of fissuring or eruption, emergency measures should be set in motion: facility shut-down, equipment decoupling, equipment removal, construction of defenses, and evacuation if necessary.

Shielding. This may consist of the use of natural features (hilltops, leeward sides of hills, etc.), or the construction of earthen, concrete or rock walls, the excavation of ditches, the covering of open yards and walkways, the reinforcement of roofs, etc., as protection against bombardment, ash falls and lava flows. Earthern berms may provide only limited diversion of flows, but afford enough time for evacuation of personnel and critical equipment.

Training. A volcanic hazard plan should be designed and implemented. A coordinator or team leader should be appointed; all employees should be given clear assignments; training exercises should be held; manuals or memoranda should be prepared and distributed; and there should be periodic inspections and drills to ensure that the established risk reduction and safety measures are adhered to and enforced. Improvements should be instituted whenever new technology and changes or expansion of operations permit.

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Based on experience elsewhere, risk to the geothermal facilities on Hawaii from volcanic activity probably is quite small. It should be possible to reduce the risk to human life to a very minimal probability. Operations in some instances may need to be curtailed temporarily, but probably need not be halted fully or permanently. No permanent damage to the resource or reservoir is likely. Individual wells, pipelines or other equipment may need to be replaced. Replacement, improved design, training, etc. may add to cost, but probably can be kept within the project economic contingency levels.

Thorhallsson (1988) has summarized the Icelandic attitude to the volcanic risk, based on their continued experience at Krafla-Namafjall and elsewhere on that volcanic island:

> "....The eruptions have provided a fresh insight into the volcanic activity of Iceland and how the geothermal fields are affected, and the Krafla project has provided a wealth of experience. Volcanic eruptions are a natural risk to many high-temperature geothermal fields, <u>and it is reassuring to know that the geothermal fields can continue to produce, even though they are only a stone's throw away from an eruption</u>. The surface installations are safe as long as they are not overrun by lava. The tectonic activity at Krafla has been uninterrupted for 13 years now, a record, and large earth dams are still being made that are intended to safeguard the buildings. An elaborate early warning system has been in place (tiltmeters, seismometers, gas detectors, fissure width gauges), that have given a few hours advance notice of an impending eruption or rifting episode...." (emphasis added).

To summarize, geothermal development may be affected by volcanic eruption; there is no precedent for assuming that geothermal development will cause volcanic activity and damage. The risk to any specific site of geothermal development to damage from volcanic activity is small and literally not calculable. Where geothermal energy has a very high degree of social acceptance in Iceland, one third of the total energy requirements are met by the resource. A pragmatic approach in Hawaii may also lead to expanding development of a reliable and cost efficient source of energy.

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TABLES

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Table 1. Comparability of the Tectonic Setting of Selected Geothermal Fields in Volcanic Island Environments

Field, Country	Tectonic Setting	Comparability to Hawaii	Evaluation of History
Piton de la Fournaise, Reunion Island, France (Indian Ocean)	Oceanic hot spot	Similar tectonic setting, geologic processes and products	Exploration has not led to development of geothermal field; volcano in almost continuous eruption.
Yellowstone, USA	Continental hot spot	Not similar geologically or in terms of volcanic processes or products	No commercial drilling allowed.
Krafla-Namafjall, Iceland	Oceanic spreading center	Similar geologic processes and products	History of developed fields is pertinent to Hawaiian conditions.
Ascension Island, UK (mid-Atlantic)	Oceanic spreading center	Similar geologic processes and products	Exploration has been unsuccessful; not relevant.
Agua de Pau, São Miguel Island, the Azores, Portugal	Oceanic spreading center	Similar tectonic setting; more highly evolved volcanic products (silicic/alkalic)	No known volcanic impact upon field development or power plant operation.
Asal, Djibouti	Triple junction; continental-oceanic spreading center	Different tectonic setting, but similar geologic processes and products	Despite success in drilling, no field development to date; 1978 eruption (lava flow) 4 to 5 miles away; no impact upon operations.

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Table 2. Major High-Temperature Fields within the Icelandic Central Rift Zone

Field	Development	Relevance
Hengill (Nesjavellir)	0.3 MW plant in operation during construction of 2 x 30 MW plants (1993-1998); extensive local use of hot water for heating.	Continuous miscroseismicity, correlated with cooling and fracturing of intrusive bodies at about 3 to 5 miles in depth; rifting event in 1789; major volcanic eruption about 2,000 years ago; system highly evolved to bimodel basaltic-silicic volcanism.
Krafla	30 MW plant, supplied by about a dozen wells; additional 30 MW plant under consideration.	Plant in operation during 1977-1985 rifting and eruptions; further events possible; prior major rifting-eruptive sequence 1724-1729 ("Fires of Myvatn" - see text.)
Namafjall (Bjarnarflag)	3 MW plant supplies power to diatomite plant; extensive use of hot water for heating.	Plant in operation during 1975-1985 rifting and eruptions; further events possible; see text.
Reykjanes	Extensive use of hot water for heating; consideration being given to extractive chemicals industry.	Zone of youthful rifting; basaltic lavas, intrusions and glassy tuffs; no volcanic impact upon operations.
Svartsengi (Sudurnes)	11.6 MW power plant (flash and binary) installed; 3.6 MW binary under consideration; extensive use of hot water for heating and industry.	Zone of youthful rifting; basaltic lavas, intrusions and glassy tuffs; no volcanic impact upon operations.

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FIGURES

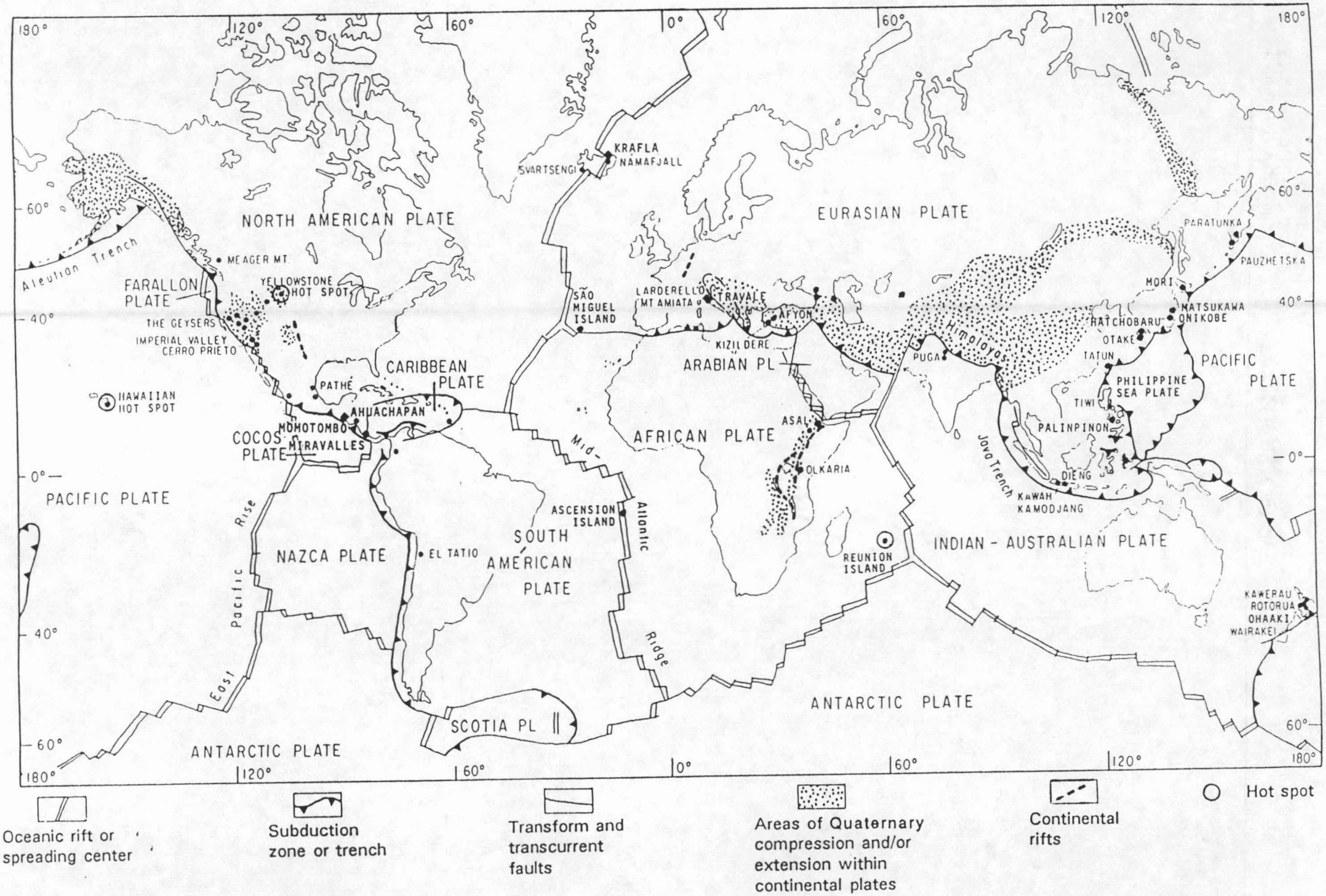

Figure 1. **Tectonic setting of geothermal fields**

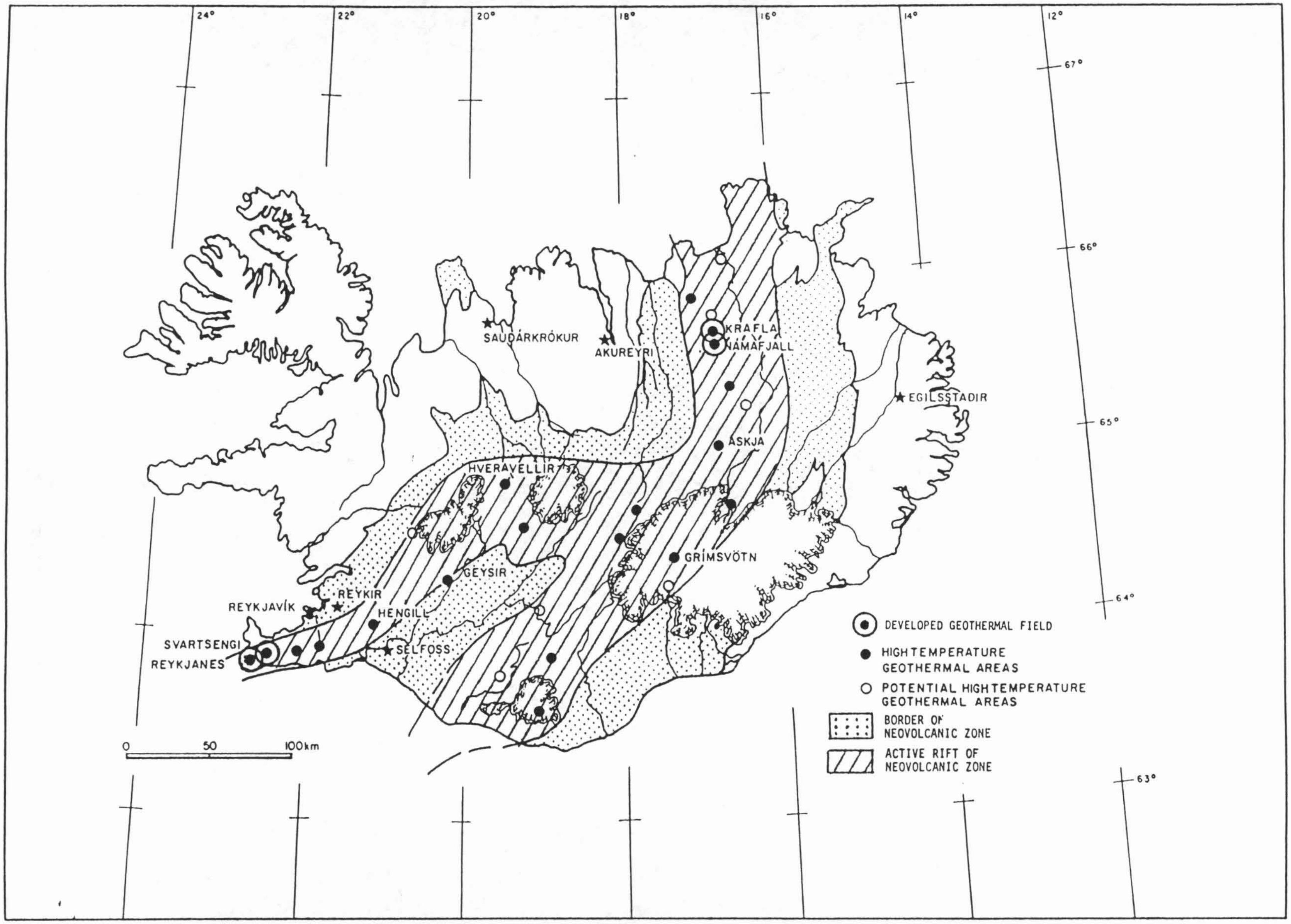

Figure 2. Geothermal areas of Iceland

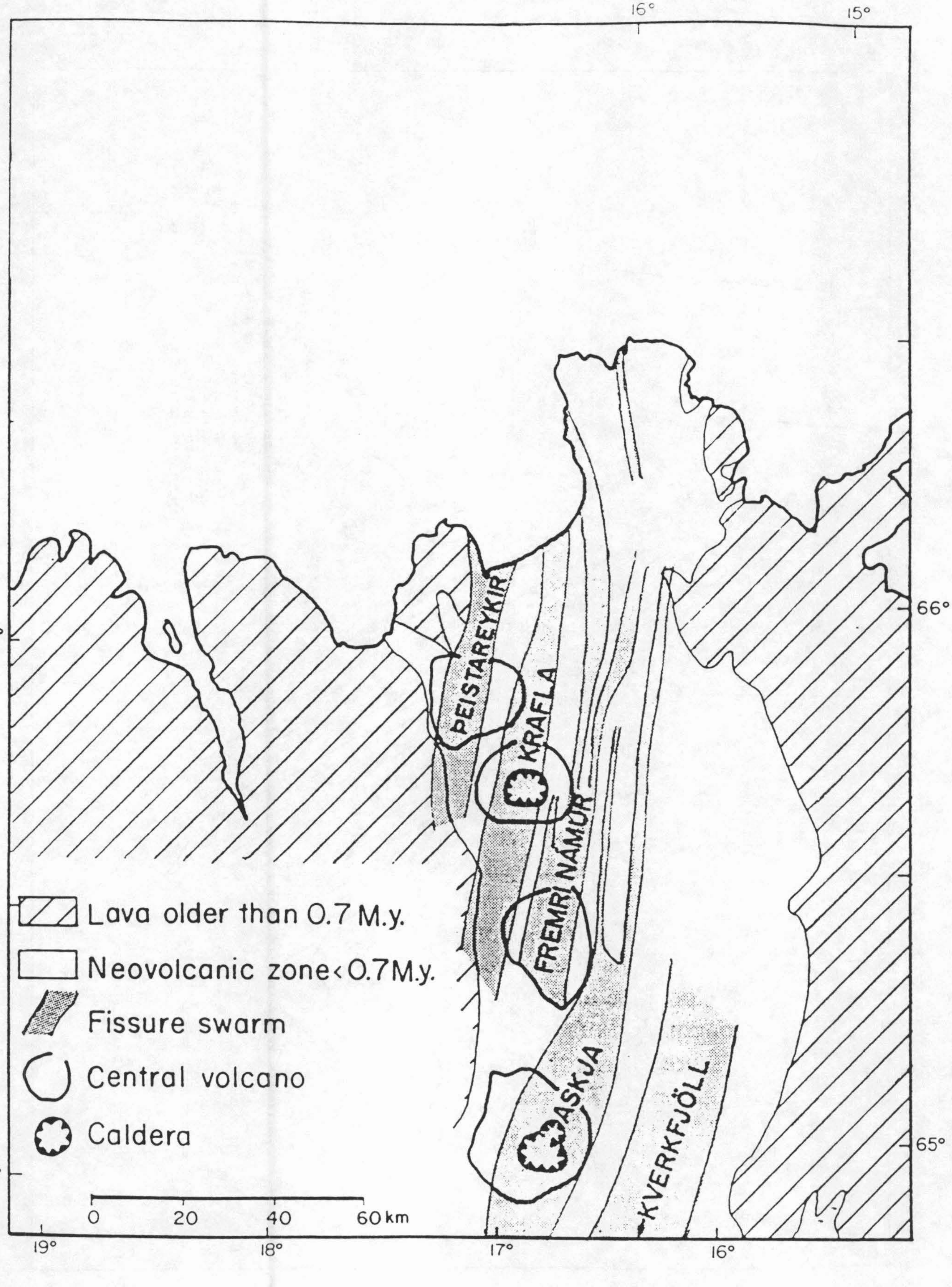

Figure 3. Location of Krafla volcano within the Neovolcanic Zone of northeast Iceland

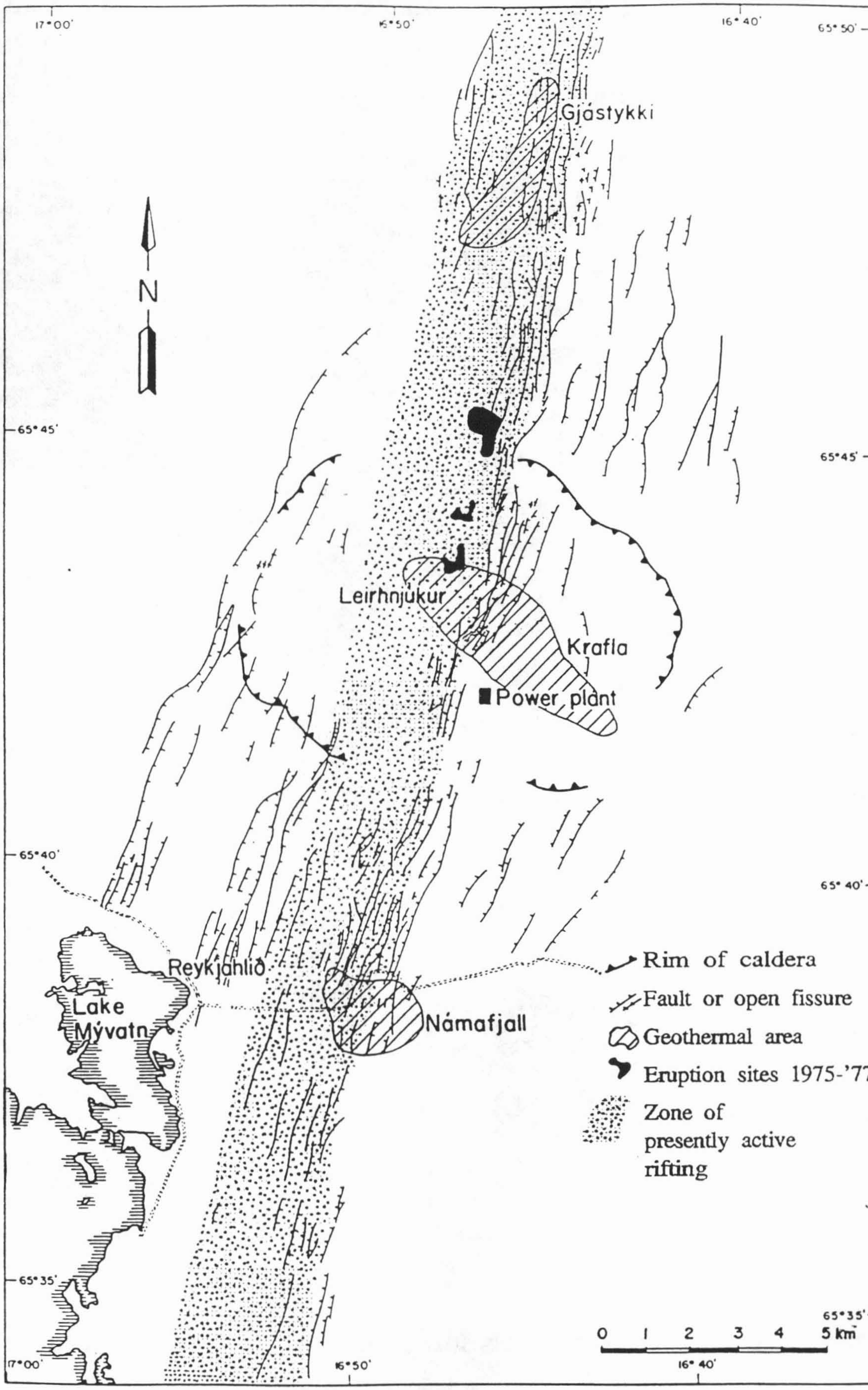

Figure 4. **Details of the Krafla and Namafjall geothermal fields**

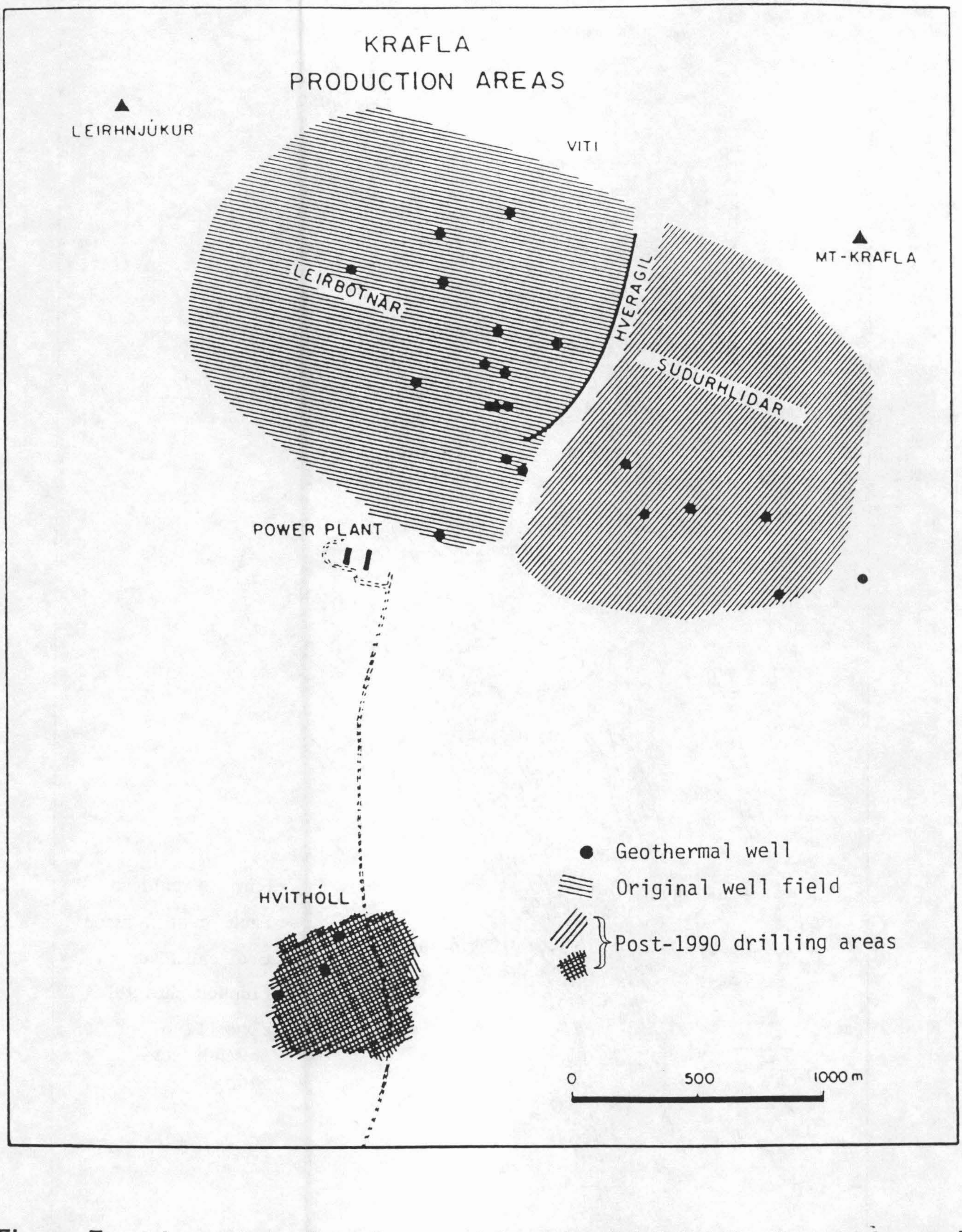

Figure 5. **Location of wells supplying the 30 MW Krafla geothermal power plant**